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WASTE DISPOSAL ON SPACE CRAFT AND ITS BEARING ON TERRESTRIAL PROBLEMS

Linvil G. Rich
Dean of Engineering, Clemson College

William Marcus Ingram
In Charge, Biological, Chemical, and Oceanographic Activities
Technical Services Branch, DWSPC
Robert A. Taft Sanitary Engineering Center

Bernard B. Berger
Assistant Division Chief for Research, DWSPC

U.S. DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE
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ABSTRACT

A completely regenerative system is outlined which would furnish the physiological requirements of humans living in an extra-terrestrial environment. Attention is focused on processes in the system which would convert organic constituents of waste to inorganic forms. An aerobic, thermophilic, microbiological process is discussed in detail in which the conversion of organics might be accomplished very efficiently. The process would be continuous and completely mixed. A large recirculation ratio would be used, and the microorganisms in the recirculated flow would be destroyed thermally. (4 figures, 18 references)

WASTE DISPOSAL ON SPACE CRAFT AND ITS BEARING ON TERRESTRIAL PROBLEMS*

INTRODUCTION

Space exploration provides man with his greatest challenge. Soon he will cross the threshold that separates the earthly womb in which his species evolved from the alien, inhospitable reaches of the universe. Yet, as he crosses that threshold he cannot throw off completely the shackles that bind him to mother earth. So adjusted is he to earth's environment, his venture into space is possible only to the extent that he can devise a similar environmental system to accompany him. Such a system, like the one on earth, must provide him with the physiological necessities of life.

Several environmental systems have been proposed. For space missions of relatively short duration, a nonregenerative system would be employed in which man's requirements would be met by stores on hand at take-off. For missions of intermediate duration, a partially regenerative system would be used. A system of this type would provide both stored and regenerated items of physiological need. Missions of extended duration would require a completely regenerative system. Possibly, such a system would involve an oxygen and carbon dioxide exchange between photosynthesizing plants and humans, waste reutilization, and the use of plants for human consumption. The chemical elements constituting the initial environment would be used again and again for human sustenance. Regeneration would require a continual input of energy.

A variety of completely regenerative systems have been proposed.[1, 2, 3, 4] While differing in detail, most are similar to the system outlined in Figure 1. For convenience of discussion, the individual unit operations and processes constituting the system are grouped according to function in one or the other of three subsystems. The culture of photosynthesizing plants, identified in the figure as the photosynthetic gas exchanger, converts carbon dioxide resulting from respiratory and chemical activity in the system to oxygen. Oxygen and the plant growth increment is consumed by man to meet his metabolic requirement. Although higher plants could serve as the photosynthetic component, only the algae have been seriously considered for use in a gas exchanger. Because of their microscopic size, algae lend themselves to manipulation under conditions that promote the greatest photosynthetic efficiency.

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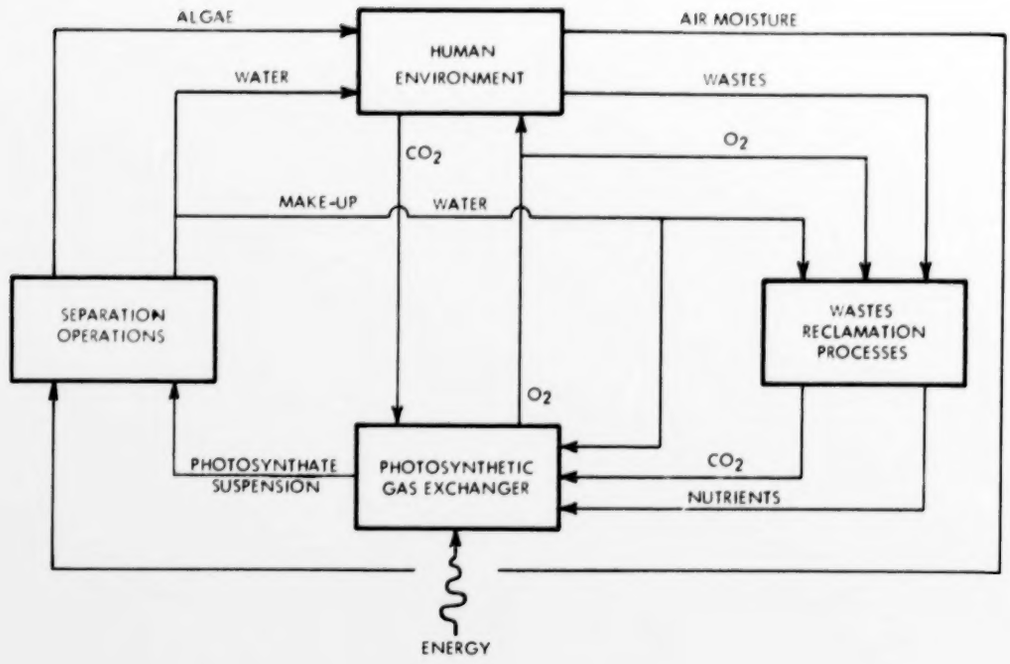

Figure 1. Regenerative system schema.

The reclamation of water from human expiration and other non-urinary sources would be accomplished in one or more operations grouped together under the heading of "Separation Operations." Purified water produced by these operations would provide drinking water to humans and furnish make-up water where needed in the system.

The reclamation of human wastes, both fecal and urinary, would be accomplished in a process or series of processes designated in Figure 1 as "Wastes Reclamation Processes." Reclamation would consist of converting the organic constituents of waste to inorganic forms. The inorganics thus produced would be used as nutrients for the photosynthate. Since the topic of concern in the present paper is waste disposal on space craft and its bearing on terrestrial problems, the discussion that follows focuses specifically on the waste reclamation processes.

WASTE COMPOSITION

The character of the waste that would be produced in a confined environment would differ markedly from a municipal sewage. Whereas, in the latter, a considerable water carriage is involved as well as a great variety of nonfecal and nonurinary pollutants, wastes generated in a confined environment would be limited to feces, urine, and limited quantities of materials resulting from ablutions, mixed together in a relatively small volume of water. The actual volume of wastes that would be treated daily per individual in the space environment would depend largely upon the extent of "luxury use" of the water supply.

The composition of urine is indicated in Table 1.[5] For a normal male, the average daily excretion of urine is somewhat in excess of 1 liter. The total solids content is approximately 5 percent by weight, of which half is urea.

Table 1. COMPOSITION OF AVERAGE NORMAL URINE DAILY EXCRETION. (HAWK, P. B., OSER, B. L. AND SUMMERSEN, H. W., PRACTICAL PHYSIOLOGICAL CHEMISTRY, THIRTEENTH EDITION, LEA AND FEBIGER, PHILADELPHIA, 1956, page 788)

Constituent	Grams
Water	1200
Solids	60
Urea	30
Hippuric Acid	0.7
Uric Acid	0.7
Creatinine	1.2
Indican	0.01
Oxalic Acid	0.02
Allantoin	0.04
Amino Acid Nitrogen	0.2
Purine	0.01
Phenols	0.2
Cl as NaCl	12.0
Na	4.0
K	2.0
Ca	0.2
Mg	0.15
S as SO_2	2.5
Inorganic Sulfates as SO_3	2.0
Neutral Sulfur as SO_3	0.3
Conjugated Sulfates as SO_3	0.2

The character and quantity of human feces varies greatly, depending upon the nature of the diet. Materials commonly found in feces are presented in Table 2. Studies indicate that from 100 to 150 grams of feces per person per day can be expected.[6] Roughly 75 percent is water, and about one-third of the solids is reported to be bacteria.[7] If the "luxury use" of water per person (wash water, food preparations, etc.) is assumed to be about 4 liters per day, a waste would be produced with an organic concentration of approximately 12,000 milligrams per liter (half of which would be urea) and an inorganic concentration of about 6,000 milligrams per liter.

Table 2. MATERIALS PRESENT IN FECES. (GRADWOHL, R. B. H., CHAPTER VIII, FECES, CLINICAL LABORATORY METHODS AND DIAGNOSIS, VOL. 2, p. 1261. C. V. MOSLEY CO., ST. LOUIS, MO. (1956).

Water	Methylmercaptan
Bacteria	Hydrogen
Tissue remnants	Carbon dioxide
Mucus	Proteoses
Detritus	Peptone
Indole	Peptides
Skatole	Ammonia
Paracresol	Amino acids
Hydrogen sulfide	

WASTE TREATMENT PROCESSES AVAILABLE

Conceivably, all processes used in the treatment of municipal sewage could be used to treat the waste generated in a confined environment. The selection of sewage treatment processes is however governed primarily by economic considerations. Processes planned for the treatment of wastes in a confined environment must be selected on the basis of compactness and reliability. These criteria emphasize high efficiencies and a fundamental knowledge of process mechanism.

Several processes, or combinations of processes, have been suggested for the waste reclamation component of a confined environment.[8] These include incineration, wet combustion, and a variety of biological processes. Recent studies have yielded information relative to the application of the incineration process to human wastes;[9] however, the high temperatures required and the difficulty of maintaining control of the process create problems greater than those likely to result from the wet combustion process. Of the biological processes available, a high rate, aerobic, completely mixed, microbiological process appears the most promising.

WET COMBUSTION

Wet combustion is an oxidation process carried out under pressure. The organic materials to be oxidized are held in a water solution or suspension. Combustion is supported by oxygen supplied by the injection of compressed air. Wet combustion temperatures are considerably lower than those required for incineration. The process fundamentals are as follows.[10]

When a water solution or suspension of organics is heated under pressure to temperatures higher than 100°C, oxidation of the organics occurs. The rate of oxidation increases as the temperature of the system is increased to the critical temperature for water (374°C). Oxidation proceeds until an equilibrium is reached. At low temperatures, equilibrium is not reached for several hours. At temperatures greater than 300°C, equilibrium is reached in a matter of minutes. The curves in Figure 2 are idealized relationships between oxidation time and the percent organic material oxidized. These curves illustrate the effect of temperature on the time required to reach oxidation equilibrium.

Oxidation ceases when equilibrium is reached. The extent to which a material is oxidized at equilibrium is a function of temperature. The effect of temperature is illustrated in Figures 2 and 3. At temperatures of 300°C or higher, a high degree of oxidation is obtained. It is to be noted from Figure 3 that, regardless of the initial concentration of the organic material being combusted, the final concentration at equilibrium will be about the same when the combustion temperature is 300° or higher.

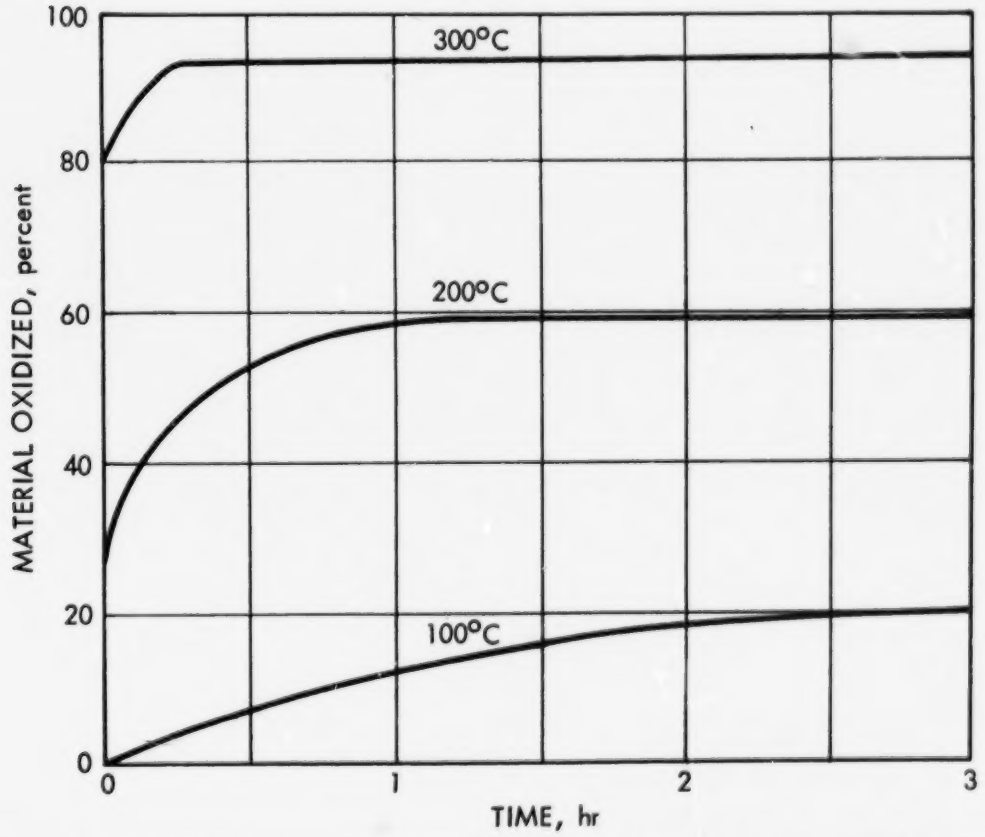

Figure 2. Effect of temperature upon time required to reach oxidation equilibrium. (Adapted from Figure 2, "Ultimate Disposal of Sewage Sludge by Wet Oxidation," E. Hurwitz and W.A. Dundas, Proceedings of Fourteenth Industrial Waste Conference, Purdue University, 1959.)

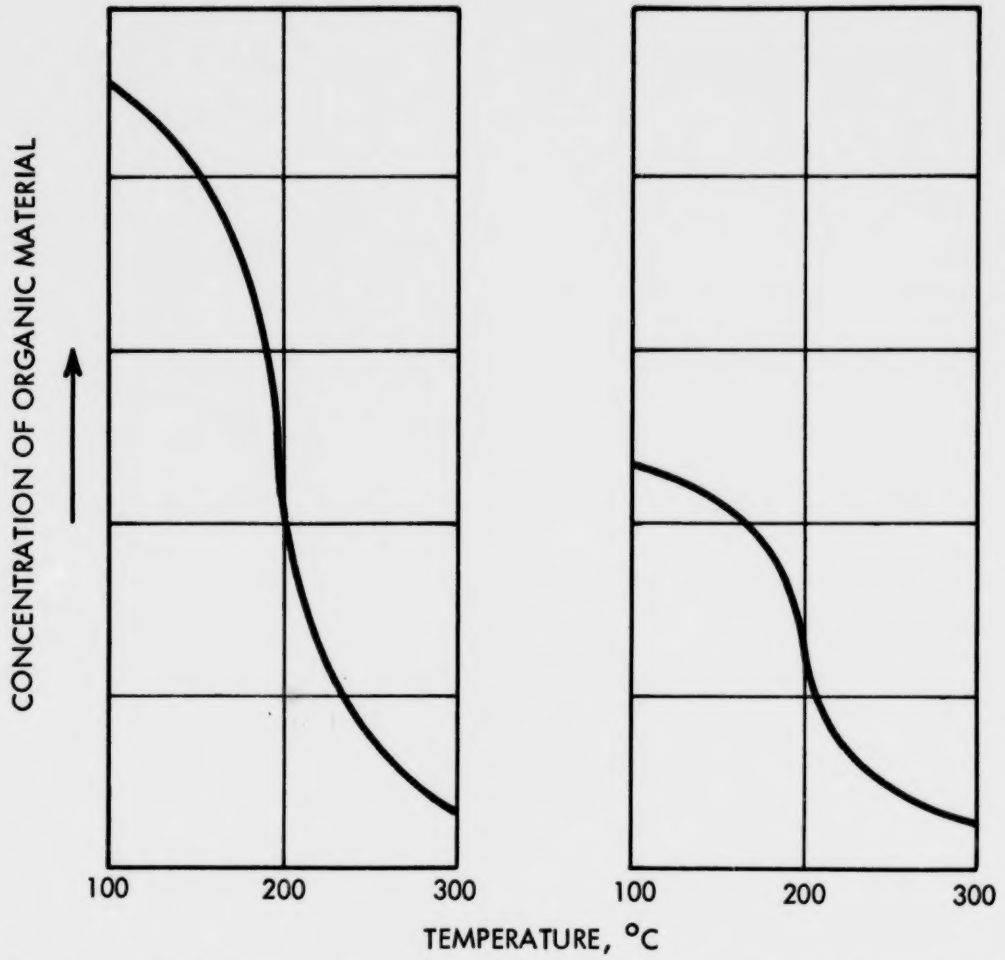

Figure 3. Effect of temperature upon oxidation of organic material at equilibrium. (Adapted from Figure 2, "Wet Air Combustion," Industrial Water and Wastes, 6 (4) 102-106, 1961.)

Oxidation of the organic material is not as complete as it is in dry combustion. Ammonia and a variety of organic compounds appear in the effluent of a wet combustion process. The quantity of oxygen required by the process can be estimated from the equation

$$C_aH_bO_cN_d + 0.5\,(ny + 2s + r - c)\,O_2 \longrightarrow$$

$$nC_wH_xO_yN_z + sCO_2 + rH_2O + (d - nz)\,NH_3 \qquad (1)$$

where $C_aH_bO_cN_d$ = initial organics

$C_wH_xO_yN_z$ = final organics

n = moles of final organics

r = moles of water produced = $0.5\left[b - nx - 3\,(d - nz)\right]$

s = moles of carbon dioxide produced = $a - nw$

Oxygen should be added to the system at a rate that will not impede combustion. Oxygen in excess of the required stoichiometric quantities does not accelerate the process. In a continuous flow

system the operating pressure ranges from 1,200 to 1,800 psi. A more detailed description of the process may be found elsewhere.[11]

The wet combustion process has found application in the disposal of sludge from sewage and industrial wastes. In this application, the process is designed to be continuous. In a confined environment, however, a batch process might be more convenient, from the standpoint of both control and cubage. Residual organics might present a problem, and possibly, would have to be removed in a subsequent process.

HIGH-RATE MICROBIOLOGICAL PROCESSES

In spite of their long application to waste treatment, aerated microbiological processes have been only partially understood. Attempts to describe the behavior of continuous-flow activated sludge systems in terms of batch-flow kinetics have produced conclusions not supported by experimental data. Inefficient aeration devices, waste peculiarities, and imperfect analytical parameters have resulted in additional ambiguities.

The kinetics of continuous-flow, completely mixed microbiological processes are only now becoming understood. The classic work by Monad,[12] followed by that of Elsworth, et al.,[13] has provided basic relationships with which we can predict the behavior of such processes. As a result, the design of a completely mixed process can now be made on a rational basis. The relationships are as follows:

$$c^* = \frac{WDK - WDc_b + k_m c_b}{k_m - WD} \qquad (2)$$

and

$$s^* = \frac{a\,(c_o - c^*)}{W} \qquad (3)$$

where

- c^* = steady-state concentration of organics in the discharge from the system
- s^* = steady-state concentration of microorganisms in the discharge from the system
- D = dilution rate, reciprocal of the theoretical retention time in the system
- c_o = concentration of organics in the influent
- k_m = growth rate constant
- K = saturation constant
- c_b = concentration of organics required to sustain the basal metabolic functions of the microorganisms
- W = fraction of the microorganisms in the discharge that is wasted and not returned to the system through recycle
- a = constant.

The constant, a, relates the growth rate of the microorganisms with the utilization of organics in a batch process.

$$ds/dt = a\left[dc/dt - (dc/dt)_b\right] \quad (4)$$

where

ds/dt = growth rate
dc/dt = rate of change in concentration of organics due to assimilation
$(dc/dt)_b$ = rate of change in concentration of organics required to sustain the basal metabolic functions of the microorganisms.

The increase in microorganism concentration over a given interval of time ($\Delta s/\Delta t$), when plotted against the decrease in concentration of organics in the system ($\Delta c/\Delta t$), results in a straight line with a slope equal to a.

In a system in which the concentration of organics is maintained at a constant level, and the ratio of organics to microorganisms is relatively low (as in activated sludge processes), the specific growth rate will vary with the concentration of organics in the system:

$$k = k_m \frac{c^* - c_b}{K + c^* - c_b} \quad (5)$$

Under steady-state conditions, the specific growth rate is controlled by the dilution rate and recycle rate, both of which are operating variables:

$$k = WD \quad (6)$$

If the dilution rate, D, is increased to a point where all microorganisms are washed out of the system,

$$k = k_m = WD_c \quad (7)$$

where

D_c = dilution rate at which microorganisms are washed out of the system.

Different values of c^* can be obtained by varying the dilution rate. These values, along with k_m, establish a series of equations (Equation 5) with two unknowns, K and c_b. The values of these constants are obtained through the solution of the equations.

A more detailed development of the preceding relationships is discussed elsewhere.[10]

Significant energy is released as heat in high-rate biological processes. During a pilot-plant investigation of the treatment of citrus waste waters by the activated sludge process, it was reported that, at one point, the unit had become "so overloaded that the heat of its own activity raised the temperature so high that serious harm was done to the microorganisms population."[14] The temperature of the mixed liquor at that time rose from an average of 90°F (32.2°C) to a minimum of 106° (41°C).

The rate at which heat is liberated in a microbiological process can be determined by a comparison of the chemical energy of the organics entering with that of the organics leaving the process. The

chemical energy can be estimated with the empirical relationship:

$$h = 127\,R + 400 \qquad (8)$$

where

h = unit heat of combustion, cal/g
R = a value expressing the degree of reduction.

The R-value of any type of organic material can be computed from an expression developed from a rational consideration of the quantity of oxygen required for the complete oxidation of all carbon and hydrogen to carbon dioxide and water:[15]

$$R = \frac{100\,[2.66\,(\%\ \text{carbon}) + 7.94\,(\%\ \text{hydrogen}) - (\%\text{oxygen})]}{398.9} \qquad (9)$$

Carbon and hydrogen combustion analyses have been found more convenient than calorimetric procedures for determining the chemical energy of organic solids.

Research on activated sludge processes at thermophilic temperatures has failed to yield information indicating greater biological activity at thermophilic temperatures than at temperatures in the mesophilic range.[16, 17] On the other hand, it has been demonstrated rather conclusively that aerobic decomposition in a composting process proceeds much more rapidly at thermophilic temperatures than at lower temperatures.[18] The failure to demonstrate increased activity in the case of the thermophilic activated sludge studies may have been caused by one, or both, of two factors. Process efficiency could have been influenced by the clarification capacity of the mixed liquor. If this was the case, increased biological activity at the elevated temperatures could have been masked by poor separation characteristics.

Reduced activity at thermophilic temperatures may have been the result of an oxygen deficiency. The oxygen saturation concentration is low at elevated temperatures, and the saturation deficit and, hence, the mass transfer rate are decreased significantly. Aeration systems that support biological activity at temperatures in the mesophilic range may become inadequate at higher temperatures. Obviously, considerable research is required to determine high-temperature effects on submerged, aerobic, microbiological systems used in waste treatment.

Cubage and weight are chief considerations in the selection of a waste treatment process to support humans in the confined environment of space travel. These considerations set the requirement for a highly efficient process. The preceding discussion of kinetics, thermogenesis, and temperature effects has been presented as information pertinent to the design of a process that would treat organic wastes at rates higher than those designs of processes currently used in waste treatment technology. The process would occupy less cubage and would have particular application to confined environments, either in marine craft or space craft, and, perhaps, to industrial waste treatment.

The process would consist of a vessel containing a mixed culture of microorganisms and a heat sterilizer. The vessel would be designed in such a way that the flow-through characteristics would approach those of a completely mixed model. A major portion of the effluent from the vessel would be recirculated following heat sterilization. A flow diagram of the process is presented in Figure 4.

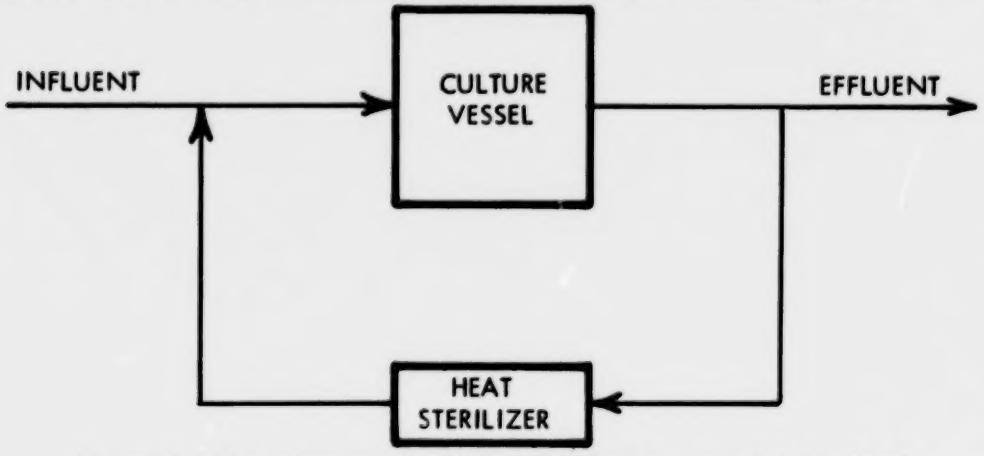

Figure 4. Flow diagram of a high rate, aerobic, completely mixed, microbiological process with sterilizer.

Since the flow-through rate would be adjustable, the ratio of the concentration of organic waste to the concentration of microorganisms in the culture vessel could be kept high and, as a result, the growth of microorganisms could be maintained in the logarithmic growth phase.

The growth rate of the microorganisms would be maximized by holding the temperature in the culture vessel at the thermophylic optimum. The culture vessel would be insulated and the heat losses would be compensated for by heat liberated from the process. Additional heat would be applied to raise the temperature of that portion of the effluent recycled to a value required to kill most of the organisms, possible 70° to 80°C (158° to 176°F). The heat sterilizer would provide the holding time necessary to attain the desired degree of kill.

Influent to the culture vessel would contain organics from the feed stream and dead microorganisms from the recycled discharge. A prolonged endogenous phase would thus be avoided. The system would be pressurized to increase the mass transfer rates required to sustain aerobic activity.

The design of the process described herein requires fundamental information presently unavailable. Clarification of several aspects of the proposed process will require extensive research. Specifically, research is required for:

1. determination of the optimum growth temperature.
2. determination of the rate at which heat would be evolved at the optimum growth temperature.
3. investigation of the time-temperature relationships for accomplishing varying degrees of microorganism kill.

The research data thus obtained would then permit the design and evaluation of an integrated system of culture vessel and heat sterilizer.

SUMMARY

Manned space missions of extended duration will require regenerative systems that provide the physiological necessities of man. Possibly, such systems will involve an oxygen and carbon dioxide exchange between photosynthesizing plants and humans, waste reutilization, and the use of plants for human consumption. The chemical elements constituting the initial environment will be used again and again for human sustenance. Regeneration will require a continual input of energy.

Solid and liquid human wastes will be processed to provide inorganic nutrients for the photosynthetic component of the system. These wastes will consist primarily of urine and fecal solids. Many processes, or combinations of processes, could be used to convert the waste organics to inorganics. Two processes hold particular promise for this purpose.

The conversion of the organics both in fecal and urinary solids or in fecal solids alone may be achieved by wet combustion. Essentially, wet combustion is an oxidation, under pressure, of organics in a water solution or suspension. Oxygen to support the combustion is supplied by the injection of compressed air. Combustion temperatures are considerably lower than those of dry combustion. The process finds present application in the disposal of sewage and industrial waste sludges.

The conversion of organics might be accomplished very efficiently in an aerobic, thermophilic, microbiological process. The process would be continuous and completely mixed. A large recirculation ratio would be used, and the microorganisms in the recirculated flow would be destroyed thermally. Such a process could have application in waste treatment systems for ships, submarines, and aircraft. Application might be made also to the treatment of concentrated, highly soluble industrial wastes.

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